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ROBINSON, James Pratt, 1934-
AUDITORY EFFICIENCY AMONG BLIND AND SIGHTED LISTENERS AS MEASURED BY SIGNAL DETECTION PROCEDURES.

Vanderbilt University, Ph.D., 1968
Psychology, experimental

University Microfilms, Inc., Ann Arbor, Michigan

AUDITORY EFFICIENCY AMONG BLIND AND SIGHTED LISTENERS AS MEASURED BY SIGNAL DETECTION PROCEDURES

By

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Dissertation

Submitted to the Faculty of the

Graduate School of Vanderbilt University

in partial fulfillment of the requirements

for the degree of

DOCTOR OF PHILOSOPHY

in

Psychology

June, 1968

Nashville, Tennessee

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CHAPTER I

INTRODUCTION

Persons with sensory handicaps may develop ways of using their unhandicapped modalities which are different from those employed by non-handicapped people. A case in point is the hearing of blind people. Recently blindfolded sighted people are relatively helpless, but many individuals who have been blind for some time move freely within their environments, hold responsible jobs, and, in some cases, serve in the professions (Bauman and Yoder, 1962; Crawford and Lirtzman, 1966; Lende, 1962). Although touch and smell are important in the environmental awareness and mobility of these people, particularly in confined spaces, hearing plays an increasingly important role as the distance between the subject and the object of concern increases. The thesis that hearing is important in mobility is supported by the .01 level correlations found by Riley, Luterman and Cohen (1964) between degree of mobility and hearing thresholds at high frequencies.

Audition is important not only in the identification of sound producing targets (automobiles, for example), but also in discriminating among echoes from targets in

order to make inferences about the bearings, ranges and textures of targets (Kellogg, 1962; Rice, Feinstein and Schusterman, 1965; Supa, Cotzin and Dallenbach, 1944). Robinson (1966) reviews the evidence for extensive use of echodiscrimination among mammals. When both blind and sighted people were subjects in echodiscrimination experiments the blind were typically superior to recently blindfolded sighted people (Ammons, Worchel and Dallenbach, 1953; Dallenbach, 1941; Kellogg, 1962; Supa, Cotzin and Dallenbach, 1944).

The question is therefore asked, "In what way does the auditory behavior of mobile blind people differ from that of unpracticed sighted people?" The difference is believed to be a matter of learning rather than a change in physiological sensitivity (Axelrod, 1959, p. 8; Kimble and Garmezy, 1963, p. 385). Hayes (1933) and Seashore and Ling (1918) reported no significant differences between blind and sighted listeners on the audiometric tests available at those times. However, sensitivity and response biases are confounded in classical psychophysical methodology (Green and Swets, 1966), so these data do not rule out some kind of "sensory compensation" as a hypothesis to be explored. (The blind listeners might actually have had greater sensitivity [larger d's] but also set higher response criteria and therefore achieved percents correct which would have been interpreted as sensitivity equal to

that of the sighted controls.) The objective of the two experiments reported in this paper was to see if the differences in auditory behavior could be explained on the basis of changes in d's and/or betas derived from a yes-no auditory signal detection task involving a single tone in noise. Three hypotheses were considered:

Hypothesis 1: Physical sensory compensation. Physical changes in the sensory apparatus are responsible for the superior performance of some blind people. Maintenance of a significantly higher d' in a blind population as compared to an equivalent sighted population over several thousand trials would tend to support the idea that "sensory compensation" does take place.

Hypothesis 2: More careful listening, learned sensory compensation. Some blind people have learned to attend and listen so that signals with low signal-to-noise ratios which would go unnoticed by inexperienced sighted people are perceived and used. A gradual increase in d' scores for a sighted group from a point below to a point equal to those of an equivalent blind group would tend to support Hypothesis 2.

Hypothesis 3: Criterion placement. Some blind persons have become more efficient at setting their response criteria so as to maximize their gains and minimize their losses (gains in terms of accomplishing their mobility objectives, and losses in terms of being overcautious or

having an accident). Significant differences in favor of the blind on measures of efficiency of criterion placement would support Hypothesis 3.

Criterion placement and blind mobility

Hypothesis 3 is favored by the present author and it is also believed that more appropriate placement is learned best by those blind people who face the mobility problems involved in getting around unfamiliar places without sighted assistance, especially those that have had a formal course in mobility.

A listener's d' sets the upper limits on his auditory efficiency, but how closely these maxima are approached is determined by where he places his response criteria (see Appendix A). For greatest efficiency the mobile blind person would need to constantly reset his criteria as signal probabilities and the values and costs of the response contingencies changed. He would be expected to set a higher criterion on a lightly travelled street or sidewalk, where the probability of signal occurrence (warning sounds or echoes from obstructions) is low, than on a busy street or badly obstructed sidewalk; and on any given street he would be expected to set a higher criterion when he was in a hurry (false alarms would be expensive) then when he was not in a hurry.

Mobility training. The Tennessee School for the Blind offers a course which involves learning to walk and

cross streets using the feel and sounds from an especially designed cane and all available non-visual cues. It has been reported that early in their training students do act in a way which could be interpreted as setting a low response criterion. That is, they will stand at the side of the street for a long time before crossing, and move slowly with frequent stops while walking on the sidewalk. Later in their training they cross the streets more quickly and move along the sidewalks with more speed and fewer stops, perhaps because they are setting higher response criteria.

Overall plan of the study

Experiments reported by Green and Swets (1966, pp. 88-90) and Ulehla (1966) indicated that when the optimal criterion is quite far to the left or right along the likelihood ratio continuum listeners typically do not move their achieved criteria high enough or low enough to maximize earnings. It would seem that if the blind are more efficient at setting their criteria this difference would show most clearly in situations where large movements of the criterion were required to maximize earnings. Therefore two experiments, modified from the pair reported in Green and Swets (1966, pp. 88-90), were planned as shown in Table 1. The dependent variables were a measure of sensitivity (d') and a measure of efficiency of criterion

TABLE 1

OVERALL PLAN OF STUDY

Variables					
	Response Values and Costs				
P. of Signal	C/R	F/A	Hit	Miss	Optimal Betas[a]
Experiment 1: Signal Probabilities					
.25	+3	-3	+3	-3	3.00
.50	+3	-3	+3	-3	1.00
.75	+3	-3	+3	-3	0.33
Experiment 2: Value-Cost Matrices					
.50	+3	-3	+1	-1	3.00
.50	+3	-3	+3	-3	1.00
.50	+1	-1	+3	-3	0.33

Note.--Financial bonus in both experiments was one half cent per net matrix point.

[a]From formula for maximizing expected value (Green and Swets, 1966, p. 23).

placement (loss in bonus earned). Loss in bonus earned is the bonus which could have been earned with optimal criterion placement, given the d', minus the bonus actually earned (see Appendix B for computational details).

CHAPTER II

EXPERIMENT 1: SIGNAL PROBABILITIES

Method

Both Experiment 1 and Experiment 2 were yes-no auditory signal detection tasks with feedback delivered after each response. Each listener was paid $1.50 per hour plus a bonus of one half cent per net matrix point. Practice and experimental sessions were two hours long, usually scheduled on successive days and each session contained five one hundred trial blocks.

Subjects. The majority of the listeners in both experiments were high school age but there were four college and two above college age listeners. Mean age and years of formal education were held approximately equal among the groups. In Experiment 1 there were six blind and six sighted male listeners. Two of the blind listeners had had a formal course in mobility.

Apparatus. An audio oscillator (Hewlett Packard Model 201 C), a noise generator (Grayson-Stadler Model 455 C), a variable frequency filter (Allison Laboratories Model 2AB), two attenuators (a locally constructed atten-

uator with two Daven decade attenuators in the noise circuit and a Hewlett Packard Model 350 C in the signal circuit), a mixer (locally constructed), an impedence matching transformer (Grayson-Stadler Model E 10589 A), and a headset monitor box (locally constructed) were arranged so as to deliver stimuli to two earphones (Grayson-Stadler Model HD 1 set in MX-41/AR earphone cushions) mounted on a headset inside a sound isolated room (Industrial Acoustics Company Model 1204 A). (See Figure 1 for a block diagram of the apparatus.) Signals and noises were gated through electronic switches (the noise through a Grayson-Stadler Model 829 E and the signal through a Grayson-Stadler Model 829 C keyed by a Grayson-Stadler Interval Timer Model 472). The sequence of events during each trial was controlled by an eight bank timer (Lafayette Instrument Company Model 1431 A) in conjunction with four decade timers (Hunter Manufacturing Company, two of them Model 100 C, and the other two Model 111 A). The frequency coming out of the audio oscillator was periodically checked on an electronic counter (Hewlett Packard Model 5223 L). Voltage readings taken from the headset monitor box with a Ballentine Model 300 H true rms voltmeter were used to set the outputs of the audio oscillator and noise generator at the beginning of each session. The signal was a 28 decibel (relative to .0002 millibars) 900

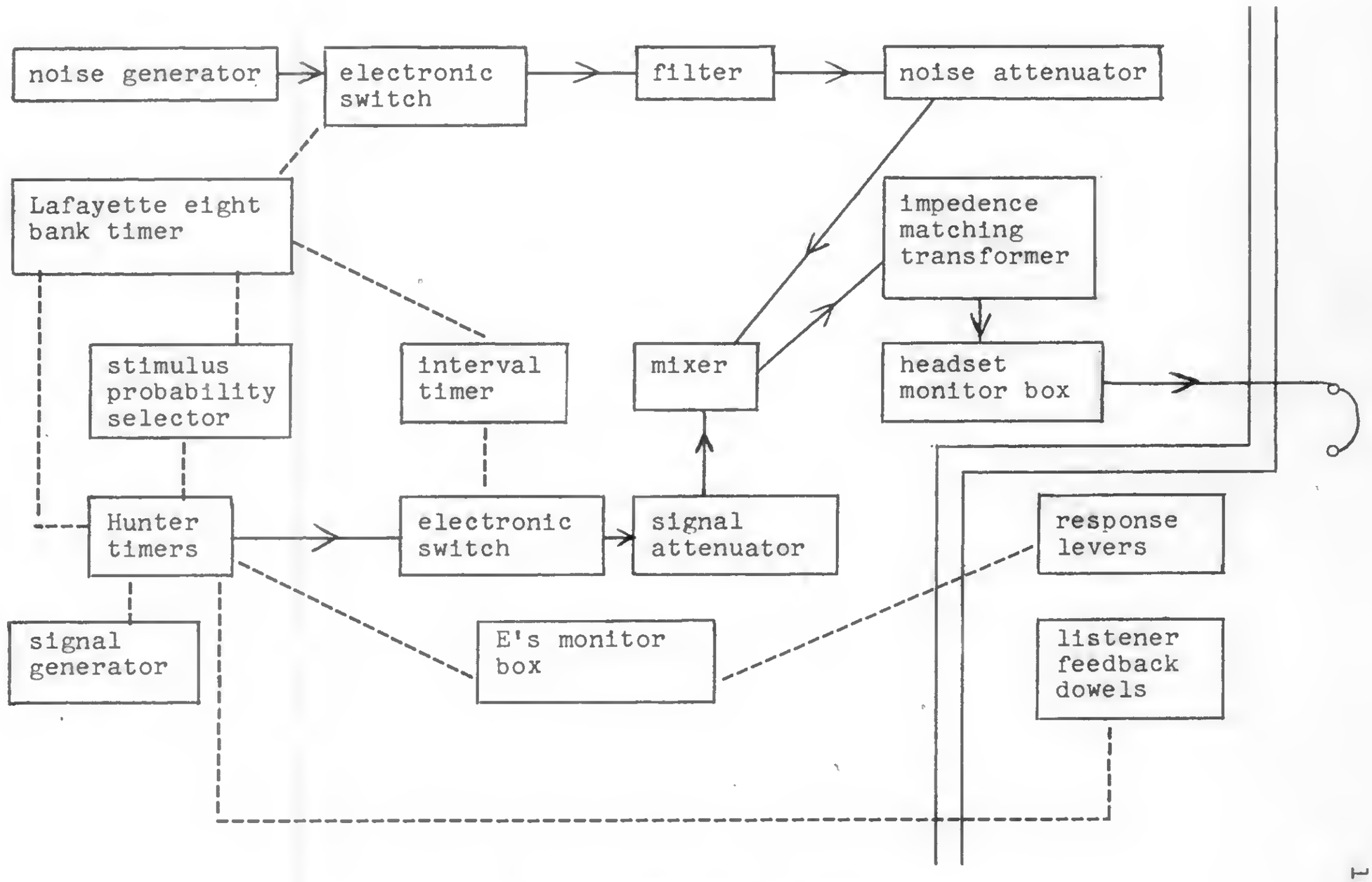

FIG. 1. Block Diagram of Apparatus

Hz tone. The noise was at 7.5 decibels (relative to .0002 millibars) per one cycle band with a bandwidth of 600 Hz (lower filter cutoff at 600 Hz, upper filter cutoff at 1200 Hz). The stimulus interval was 7.2 seconds, divided as follows: (a) filtered noise for 2.2 seconds, with .10 second signal occurring after 1.1 second on a randomly chosen 25, 50, or 75 percent of the trials, (b) response interval of 3.1 seconds, (c) a feedback interval of 0.5 second, (d) a 1.4 second interval during which the tape in the stimulus probability selector moved to the next position. Signal probabilities were determined by which of the three punched tapes was fed into the stimulus probability selector. Feedback was delivered via wooden dowels, one of which vibrated after a signal was given, the other after a noise.

Experimental design. Each listener served in a practice session with optimal beta equal to 1.00, followed by three experimental sessions in which optimal betas of 0.33, 1.00, or 3.00 were employed. The order of the experimental treatments was counterbalanced among the listeners (see Appendix C for table showing experimental design).

Procedure. Instructions which explained the task and described the procedure whereby bonuses could be earned were read to the listener at the beginning of the practice session (see Appendix D for instructions). At the begin-

ning of each experimental session listeners were told only what the probability of signal would be (.25, .50, or .75) for that session. At the end of each block of 100 trials the listener had a short rest period during which he was told his percent correct, the number of correct rejections, false alarms, hits, misses, and the amount of bonus earned.

CHAPTER III

EXPERIMENT 2: VALUES AND COSTS

Method

Subjects. Four blind people who had had a formal course in mobility, four blind people who had not had a formal course in mobility, and four sighted people worked in this experiment. Half of the listeners in each group were female.

Apparatus. Equipment was basically the same as that used in Experiment 1, except that only the .50 probability of signal tape was used (see Appendix C for explanation of a small change that was made in the apparatus).

Experimental design. Each listener in each group served in a practice session with optimal beta equal to 1.00, than in two experimental sessions with optimal betas of 0.33 and 3.00. The order of experimental treatments was counterbalanced among the listeners (see Appendix C for table of experimental design). Note that the experimental treatment in which beta equals 1.00 was not rerun in Experiment 2 because it had already been run in Experiment 1.

Procedure. The sequence of events was basically the same as in Experiment 1 except that at the beginning of each session the listeners were shown a matrix card which was appropriate for that session (see Figure 2 for examples of these cards). The blind listeners used cards embossed in Braille. Instructions explaining the card and the bonuses were presented by an audio tape.

Sessions in Which Optimal Beta = 0.33

	RESPONSES	
	SIGNAL	NOISE
signal	HIT +3	MISS -3
noise	FALSE ALARM -1	CORRECT REJECTION +1

Sessions in Which Optimal Beta = 1.00

	RESPONSES	
	SIGNAL	NOISE
signal	HIT +3	MISS -3
noise	FALSE ALARM -3	CORRECT REJECTION +3

Sessions in Which Optimal Beta = 3.00

	SIGNAL	NOISE
signal	HIT +1	MISS -1
noise	FALSE ALARM -3	CORRECT REJECTION +3

FIG. 2. Matrix Cards for Experiment 2

CHAPTER IV

RESULTS

Each table entry from Experiment 1 represents 3000 trials (five hundred trials from each of six listeners). Each table entry from Experiment 2 represents 2000 trials (five hundred trials from each of four listeners). Table 2 shows the mean d's for all the groups in all the treatments. The largest differences were tested with analyses of variance and no significant differences were found between the blind and sighted groups (see Appendix E for summary tables). There is a trend in Experiment 1 for mean d's to increase with the optimal betas, but the difference between the extreme means was not significant (by direct difference method t [5] = 1.88).

Table 3 shows a tendency for the d's in all groups to increase from the first to the second experimental session, significantly in the case of the nonmobile blind (by direct difference method t [3] = 3.60, $p < .05$). Table 4 shows no significant differences between the blind and sighted groups in losses in bonus earned (the largest difference was between the mobile and nonmobile blind in

TABLE 2

MEAN d's

Group	Optimal Betas				
	0.33	1.00	3.00	$\bar{X}$	SD
Experiment 1: Signal Probabilities					
Sighted	0.81	0.79	0.92	0.84	0.31
Blind	0.69	0.85	1.01	0.85	0.44
$\bar{X}$	0.75	0.82	0.96	0.85	
SD	0.37	0.40	0.56		
Experiment 2: Values and Costs					
Sighted	0.92		0.88	0.90	0.15
Mobile Blind	0.75		0.79	0.77	0.21
Nonmobile Blind	0.96		1.01	0.98	0.38
$\bar{X}$	0.88		0.89	0.89	
SD	0.32		0.23		

TABLE 3

MEAN d's, TREATMENTS IN ORDER

Group	Treatment Order				
	1	2[a]	3	$\bar{X}$	SD
Experiment 1: Signal Probabilities					
Sighted	0.72	0.90	0.91	0.84	0.31
Blind	0.83	0.96	0.76	0.85	
$\bar{X}$	0.77	0.93	0.83	0.85	
SD	0.42	0.38	0.32		
Sighted	0.89	0.92		0.90	0.15
Mobile Blind	0.75	0.79		0.77	0.21
Nonmobile Blind	0.85	1.12*		0.98	0.38
$\bar{X}$	0.83	0.94		0.89	
SD	0.32	0.23			

[a]Comparison to first treatment.

*$p > .05$.

TABLE 4

MEAN LOSSES IN BONUS EARNED

Group	Optimal Betas				
	0.33[a]	1.00	3.00	$\bar{X}$	SD
Experiment 1: Signal Probabilities					
Sighted	1.37	0.20	0.20	0.59	0.75
Blind	1.33	0.16	0.27	0.59	0.88
$\bar{X}$	1.35**	0.18	0.24	0.59	
SD	0.98	0.25	0.34		
Experiment 2: Values and Costs					
Sighted	1.24		0.50	0.87	0.51
Mobile Blind	1.20		0.85	1.03	0.38
Nonmobile Blind	1.63		0.41	1.02	0.68
$\bar{X}$	1.36**		0.59	0.98	
SD	0.39		0.37		

[a]Comparison with mean of 3.00 treatment.

**$p < .01$.

the 3.00 treatment, $t[6] = 1.66$). Losses were significantly greater during the 0.33 treatments than they were in the 3.00 treatments in both Experiments 1 and 2 (by direct difference method $t[11] = 3.35$, $p < .01$ in Experiment 1; $t[11] = 4.84$, $p < .01$ in Experiment 2). These differential losses reflect the pattern of criterion placement shown in Figure 3. The expected mean placement of the achieved criterion for the 0.33 and 3.00 treatments in Experiments 1 and 2 would be at the intersection of the noise and signal curves where beta would equal 1.00. The mean achieved beta for the four groups shown in Figure 3 was 1.37, indicating that the listeners tended to set their criteria too far to the right, thus increasing their losses in the 0.33 treatment. Figure 3 also shows that listeners in Experiment 1 moved their achieved criteria more toward the optimal positions than those in Experiment 2, but neither group moved them far enough to maximize their bonuses.

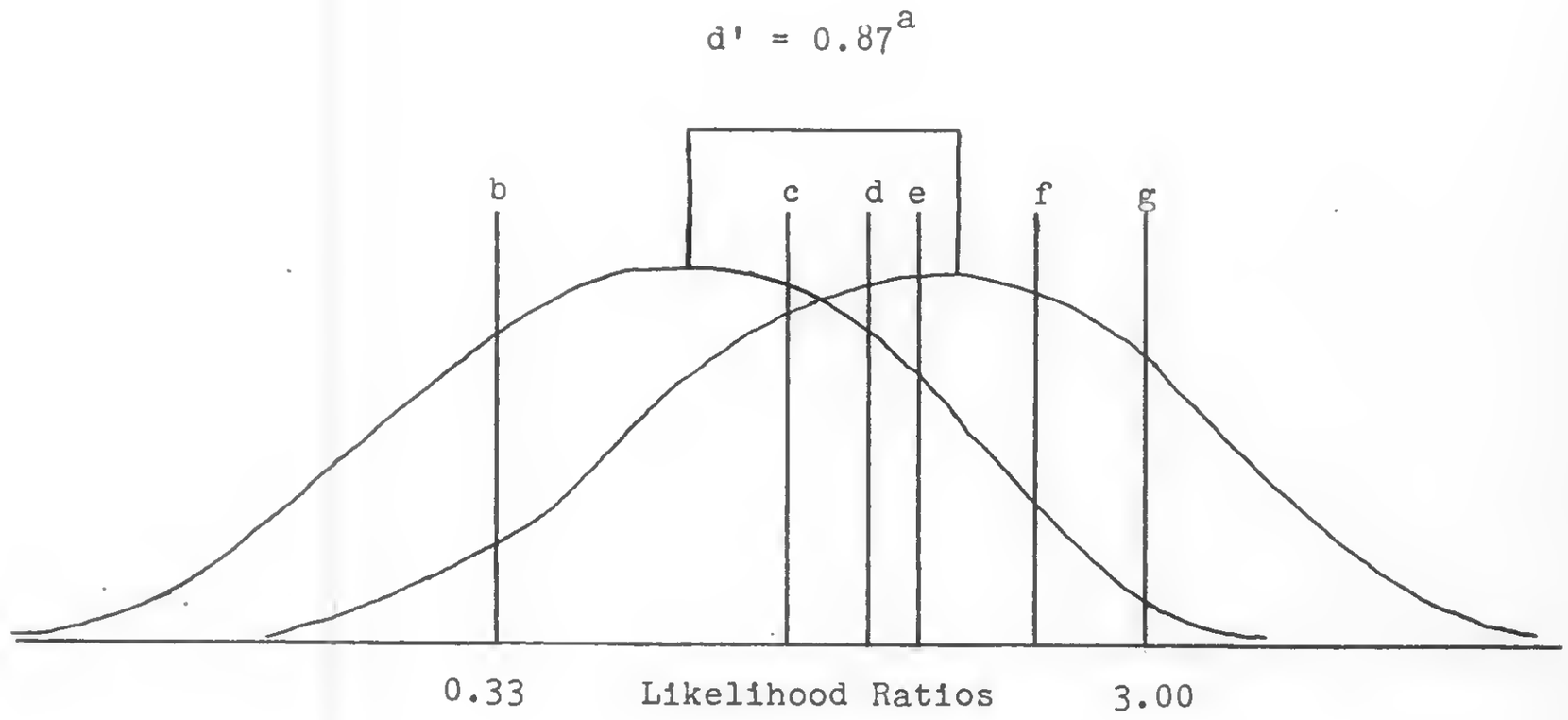

FIG. 3. Criterion Placements

[a]Mean d' of all listeners.

[b]Optimal placement, given the d', for beta = 0.33.

[c]Mean placement in Experiment 1, 0.33 treatments, achieved beta = 0.96.

[d]Mean placement in Experiment 2, 0.33 treatments, achieved beta = 1.19.

[e]Mean placement in Experiment 2, 3.00 treatments, achieved beta = 1.35.

[f]Mean placement in Experiment 1, 3.00 treatments, achieved beta = 1.99.

[g]Optimal placement, given the d', for beta = 3.00.

CHAPTER V

DISCUSSION

The results do not support any of the hypotheses proposed. No sustained differences in d' were found between the blind and sighted as predicted by Hypothesis 1. No initial difference in d', disappearing over trials was noted as predicted by Hypothesis 2, and no significant differences in efficiency of criterion placement between the sighted, mobile blind and/or nonmobile blind groups were noted as predicted by Hypothesis 3. One must conclude either that blind superiority is not based on differences in d's or betas, or that this particular experiment was not able to measure those differences.

The significant increase in d's from the first to the second experimental session among the nonmobile blind is difficult to explain. It is unlikely that it was just a chance variation because the other four groups (blind and sighted in Experiment 1, mobile blind and sighted in Experiment 2) all showed trends in the same direction. A learning effect also seems unlikely. Listeners in the experiments reported here had 1000 trials before the begin-

ning of the second experimental session. Campbell (1965) found that learning of forced-choice tasks was essentially complete after the first dozen trials, and Swets and Sewall (1963) found it essentially complete after the first three hundred trials. It may be that the listeners "paid more attention" to their criterion placements than to maintaining their d's during the first session, but concentrated on their d's during the second session.

The listener in a yes-no experiment with beta considerably different from 1.00 is faced with the two-fold task of (a) achieving and maintaining as large a d' as possible and, (b) setting his response criterion in the most appropriate position. It may be that intense concentration is required to maintain achieved d's at the upper limits set by the physiology of the organism and that attention given to anything else, by decreasing this concentration, lowers the d' from the maximum. During the first experimental session listeners may have given a large portion of their attention to trying to set their response criteria most appropriately, thereby allowing their d's to drop down from the maximum achievable. Since only relatively small movements of the criterion occurred in the experiments reported here, listeners could increase their earnings almost as much by raising their achieved d's as they could by moving their response criteria from the

preferred position to that usually achieved. The situation in Experiment 2 would be particularly confusing for the listeners who only dimly understood how the bonuses were computed, because setting one's criterion so as to maximize bonuses paradoxically lowers the achieved percentage correct. Therefore listeners may have decided toward the end of the first session and the beginning of the second session that it was more expedient to concentrate on the simpler and seemingly more logical procedure of maintaining d's as high as possible.

For a time it was thought that greater concentration on criterion placement during the first experimental session might have led to greater variability in placement which would artificially lower the d's (Carterette, Friedman and Wyman, 1966). The variability among the five interim achieved betas of each 500 trial session for the nonmobile blind were therefore computed. No consistent pattern could be discerned (see Appendix E for a table of these standard deviations). Therefore, if the listeners were concentrating more on criterion placement during the first session some strategy other than consistent trials of the criterion in different positions was being employed.

The trend for d's to increase with optimal betas in Experiment 1 is of some concern even though it did not reach statistical significance, because it is so directly

contrary to the theoretical position (Green and Swets, 1966) that d' is independent of criterion placement. This trent might also be due to the differential concentration of the listener noted above. It may be that the lower bonuses achieved in the 0.33 treatments, relative to the 3.00 treatments, led the listeners to concentrate relatively more on criterion placement in these treatments at the expense of d' maintenance.

The effects of differential concentration by the listener could be checked in a new experiment by arranging instructions or reward schedules so as to emphasize either d' maintenance or appropriate criterion placement.

Listeners in signal detection experiments are often well trained, so it is useful to have some insights into how minimally trained listeners approach the task. The strong tendency for the listeners to maintain low false alarm rates by setting relatively high criteria, and the fact that with equal knowledge of the independent variables listeners seem to adjust their criteria more to changing signal probabilities than to values and costs should be taken into account in further research or attempts to make practical applications of these techniques.

CHAPTER VI

SUMMARY

It had been hypothesized that the superiority of some blind listeners to unpracticed sighted controls on auditory mobility and echodiscrimination problems was a function of either larger d's (sensory compensation) or more efficient placement of response criteria. Two yes-no auditory signal detection experiments were conducted using a total of 14 blind and 10 sighted listeners. Optimal betas of 0.33 and 3.00 were produced by varying signal probabilities and the values and costs of the response contingencies. No significant differences were found between groups of mobility trained blind, nonmobility trained blind, and sighted listeners in either d's or efficiency of criterion placement. All groups were significantly more efficient at criterion placement in the 3.00 than in the 0.33 treatments.

APPENDIX A

LOSSES DUE TO POOR CRITERION PLACEMENT

In any yes-no auditory signal detection task there is always one point along the continuum of likelihood ratios (decision continuum) which is optimal for the response criterion. That is, if the criterion is placed at that point, percent correct or bonuses will be as high as they can possibly be, given the d'. This position can be determined with the help of the beta formula (see Appendix B) which takes into account the a priori probability of signal occurrence and the values and costs of the various response contingencies to give an optimal beta. Betas are likelihood ratios, so the actual position in standard deviation of the noise distribution units on the decision continuum can be computed if the beta and the d' are known (see Appendix B).

If the optimal beta is near one extreme of the decision continuum and the listener places his response criterion (achieved beta) nearer to the other extreme, losses can be surprisingly large. An extreme example is shown in Figure 3. In Experiment 1 listener T. D. could have, with his d', made 75 percent correct and earned a

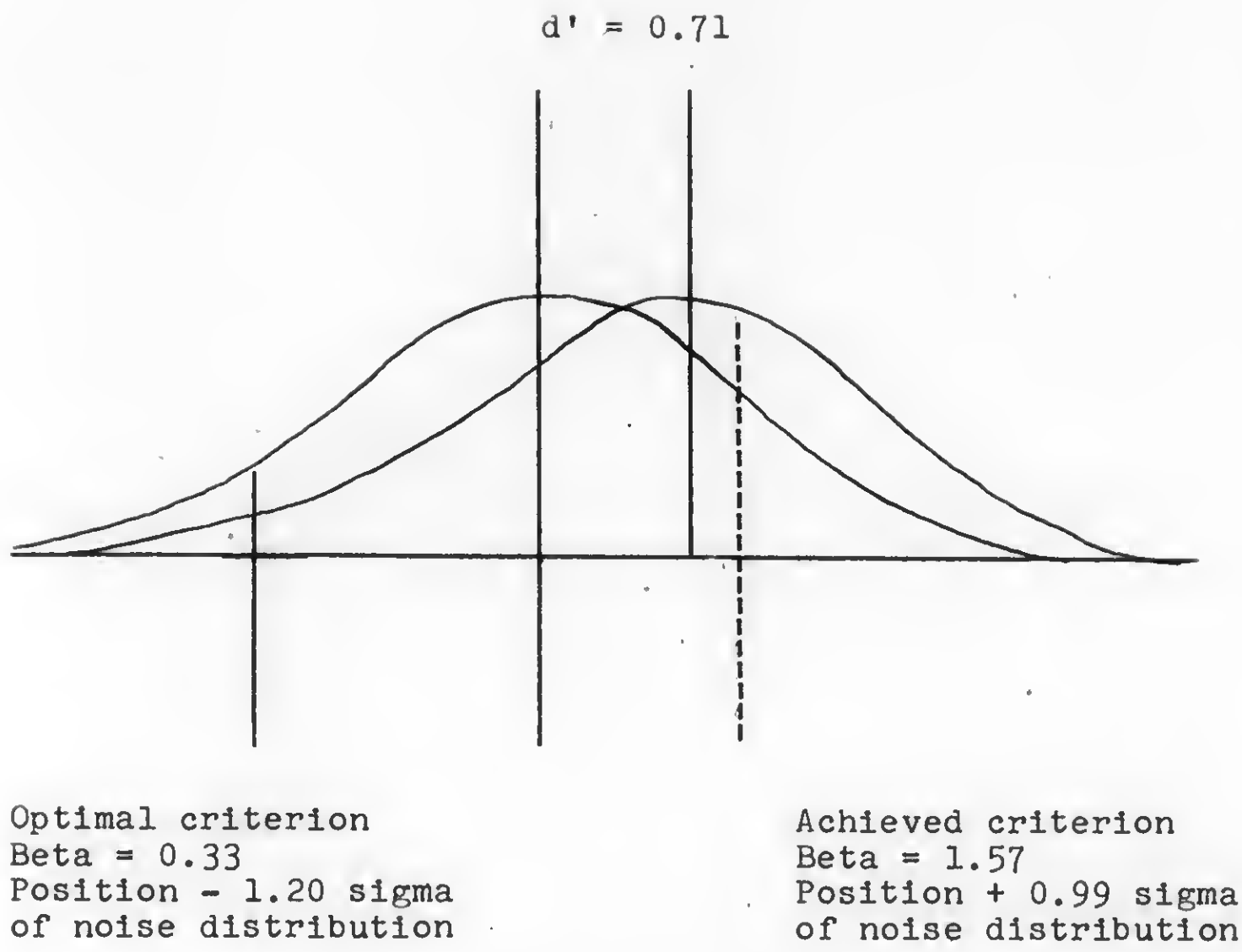

FIG. 4. An Example of Very Poor Criterion Placement

bonus of 75 cents, but due to very poor criterion placement, he made 51 percent correct and earned only a three cent bonus.

Figure 4 presents the bonuses earnable with optimal placement of the response criterion, given the d', for the treatment used in Experiment 1 in which optimal beta equals 1.00. The dotted line along the zero abscissa denotes the fact that no bonuses will be earned if the listener always says "signal" or always says "noise," or guesses (with the headset removed) on each trial. Figure 5 shows the situation in Experiment 2 when optimal beta equals 0.33 or 3.00. The broken line across the $2.50 abscissa marks the earnable bonus if the listener always says "signal" (in the treatment where beta equals 0.33), or always says "noise" (in the treatment where beta equals 3.00), that is, if his achieved betas are set at the very bottom (achieved beta nearly zero) or at the very top (achieved beta nearly infinity) of the likelihood ratio or decision continuum when that direction of movement is appropriate. The solid line indicates the bonuses earnable, given the d', with optimal criterion placement. The dotted line marked "achieved beta = 1.00" shows the bonuses earnable if the listener set his criterion at the intersection of the signal and noise curves. If the listener set his response criterion at the wrong end of the decision continuum, at the high end in the 0.33

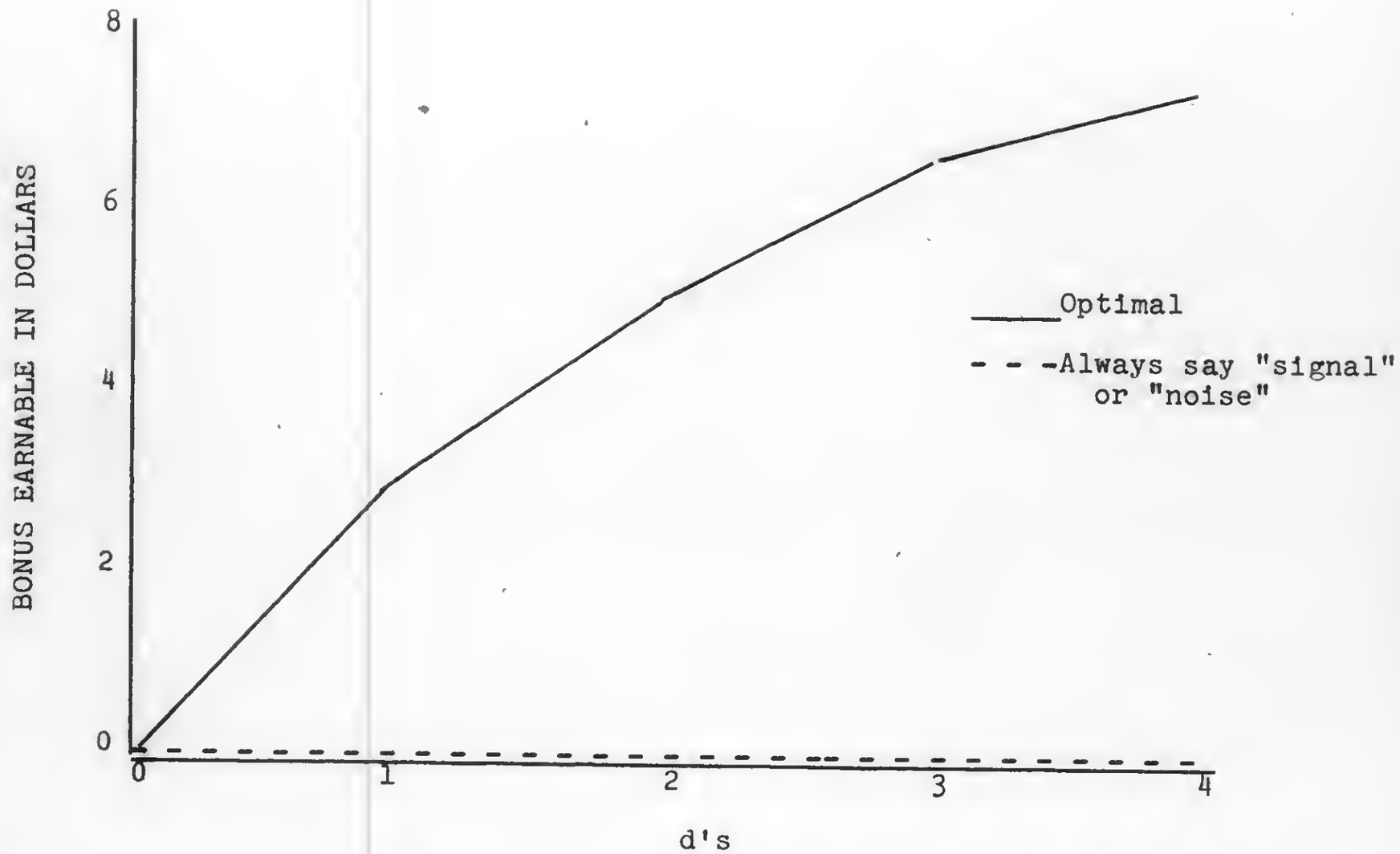

FIG. 5. Optimal Earnable Bonuses Given the d's for the Treatment in Experiment 1 in Which Optimal Beta = 1.00

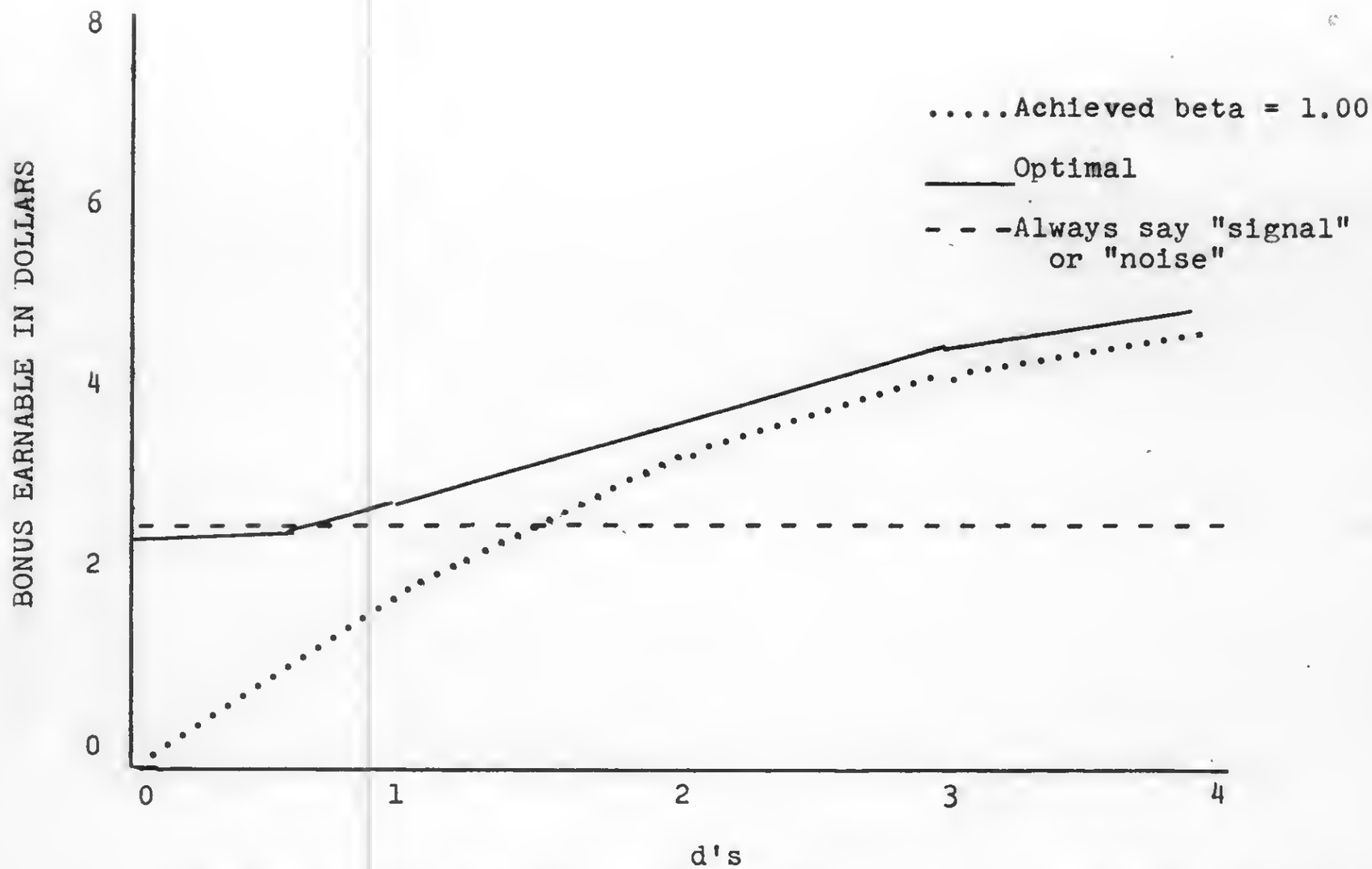

FIG. 6. Optimal Earnable Bonuses Given the d's for the Treatments in Experiment 2 in Which Optimal Betas = 0.33 and 3.00

treatment or the low end in the 3.00 treatment, or guessed randomly on each trial, he would make no bonuses at all.

It was, of course, hoped that experience at criterion placement in the molar situation of the outside world would transfer to our rather molecular laboratory task. Once the values and costs of the experiment were set up, a d' was sought that would permit the listeners to do better with appropriate placement than they could by setting what might be called the "ultimate" criterion and always saying "signal" or always saying "noise." As one can see from Figure 5, this necessitated a d' or more than .50. On the other hand it was also required that they do better with the appropriate criterion than with what was thought to be the "customary" criterion of 1.00. Figure 5 shows that the d' could therefore not be much more than 1.50. A d' of 1.00 would be about right. The actual mean d' of Experiments 1 and 2 was .87, and, as it turned out, none of the 24 listeners set an "ultimate" criterion, so it would have been better to use an even smaller d'.

APPENDIX B

COMPUTATION OF SENSITIVITY AND EFFICIENCY MEASURES

Percent correct

The number of correct rejections, false alarms, hits, and misses was recorded for each listener in each block of trials, and for each of the five hundred trial sessions. Percent correct was the sum of the correct rejections plus the hits divided by 500.

Bonuses earned

Even matrix (C/R = +3; F/A = -3; Hits = +3; Misses = -3). The number of correct rejections, false alarms, hits, and misses are each multiplied by 3. The minuses are subtracted from the plusses to produce the net matrix points. Bonus is one-half cent per net matrix point.

High matrix (C/R = +3; F/A = -3; Hits = +1; Misses = -1). The number of correct rejections and false alarms are each multiplied by 3, and the number of hits and misses are each multiplied by 1. The minuses are subtracted from the plusses to produce the net matrix points. Bonus is one-half cent per net matrix point.

Low matrix (C/R = +1; F/A = -1; Hits = +3; Misses

= -3). The number of correct rejections and false alarms are each multiplied by 1, and the number of hits and misses are each multiplied by 3. The minuses are subtracted from the plusses to produce the net matrix points. Bonus is one-half cent per net matrix point.

Conditional probabilities of false alarms and hits

Conditional probability of false alarms is the number of false alarms divided by the number of noises. It is the area of the hypothetical noise curve to the right of the response criterion.

Conditional probability of hits is the number of hits divided by the number of signals. It is the area of the hypothetical signal curve to the right of the response criterion.

Sensitivity measure, d'

By entering the tables of d' (Elliott, 1964) with the conditional probability of false alarms and hits, the d' can be read directly. It is the distance, in standard deviation of the noise distribution units along the decision continuum, between the means of the hypothetical noise and signal curves. It increases with greater ability of listeners to discriminate between signals and noises.

Computation of d' from a normal curve table. The d' can be computed directly with the aid of a normal curve

table when the standard deviation of the hypothetical noise and signal curves are arbitrarily taken as unity. Since some later computation will use similar principles, the method will be reviewed here.

(1) Locate the achieved criterion relative to the mean of noise distribution. Enter the area under the curve column of a normal curve table with the conditional probability of false alarms and read the position of the ordinate which would leave that much area above, or to the right of, the ordinate. For example, if conditional probability of false alarms is .16, an ordinate which left that much area to the right would be located at +1.00 z score of noise units. This is the location of the achieved response criterion relative to the mean of the hypothetical noise distribution.

(2) Locate the achieved criterion relative to the mean of the signal distribution. Enter the area under the curve column with the conditional probability of hits and read the position of the ordinate which would leave that much area above, or to the right of, the ordinate. For example, if conditional probability of hits is .84, an ordinate which left that much area to the right would be located at -1.00 z score of signal units. This is the location of the achieved response criterion relative to the mean of the hypothetical signal distribution. Now

that the distance of the achieved criterion from each mean is known it is easy to compute the distance between the means themselves. In this instance the mean of noise was one z score unit below the criterion; the mean of signal was one z score unit above the achieved criterion. Therefore the means are two z score units apart, and d' equals 2.

Optimal betas

Optimal betas are computed from the formula for maximizing returns (beta formula) presented in Green and Swets (1966, p. 23).

$$\text{Beta} = \frac{(V_{00} + V_{01})\ P(h_0)}{(V_{11} + V_{10})\ P(h_1)}$$

$P(h_0)$ = the a priori probability of noise

$P(h_1)$ = the a priori probability of signal

V_{00} = value associated with correct rejections

V_{01} = value (cost) associated with false alarms

V_{11} = value associated with hits

V_{10} = value (cost) associated with misses

1. If the values and costs are equal (as they were in Experiment 1), they cancel out and only the right hand part of the equation is used. (a) If probability of signal occurrence is .25, then optimal beta = .75/.25 = 3.00. (b) If probability of signal occurrence is .50, then optimal beta = .50/.50 = 1.00. (c) If probability of signal

occurrence is .75, then optimal beta = .25/.75 = 0.33.

2. If the signal probability is .50, but the values and costs are unequal (as they were in Experiment 2), only the left hand part of the equation is used. (a) If the value of a correct rejection is set at 3, the cost of each false alarm at 3, the value of each hit at 1, and the cost of each miss at 1, then optimal beta will equal 3.00: 3 + 3 / 1 + 1 = 3.00. Note that the values and costs are used in the beta formula as absolute values, e.g. the cost of a miss is 3 (not -3). However, when figuring out the bonuses for the listeners, costs are of course negative values. It is convenient to write the matrix shown above (and the other matrices) in the form +3 -3 +1 -1. (b) If the matrix is +3 -3 +3 -3, then optimal beta will equal 1.00: 3 + 3 / 3 + 3 = 1.00. (c) If the matrix is +1 -1 +3 -3, then optimal beta will equal 0.33: 1 + 1 / 3 + 3 = 0.33.

Positions of optimal betas. In terms of the hypothetical signal and noise curves, betas are likelihood ratios, specifically the likelihood that a particular observation (rate of neural firing, probably) was produced by a signal divided by the likelihood that the same observation was produced by noise alone. The height of the ordinates at any point on the signal or noise curves represents these likelihoods, so a ratio can be computed for any

point by simply dividing the height of the signal ordinate by the height of the noise ordinate at the same point. Without looking in a normal curve table for the heights of the ordinates one can say that the point where the two curves intersect will have a likelihood ratio (beta) of 1.00. Points to the right of the intersection will have likelihood ratios (betas) greater than 1.00, and points to the left will have likelihood ratios less than 1.00.

The d' must be taken into account when computing the actual position of any beta because betas move closer to the mean of noise as d' increases. Given a particular d' there is only one point on the decision continuum which will produce any particular likelihood ratio. By computing the ratios of the heights of the signal and noise ordinates at various distances from the mean of noise, the position of the likelihood ratio can be localized: (a) For beta = 3.00 with a d' of 1.00 reference to a normal curve table produces the data shown in Table 5. Therefore the location on the decision continuum of beta = 3.00, with a d' of 1.00, is +1.60 z score units above the mean of the noise distribution. (b) Computed in the same manner beta = 0.33 is at -0.60 z score units below the mean of the noise distribution.

Optimal percents correct. When the z score position of the optimal beta and the d' are known, the optimal per-

TABLE 5

POSITION OF BETA = 3.00 WITH d' = 1.00

Z score of n	Height of ordinate	Ratio of heights	Height of ordinate	Z score of s
1.59	.1127	2.97	.3352	0.59
1.60	.1109	3.00	.3332	0.60
1.61	.1092	3.03	.3312	0.61

cent correct can be computed as shown in Tables 6 and 7. The area under the noise curve to the left of the criterion is the conditional probability of correct rejections; the area to the right of the criterion is the conditional probability of false alarms. If the actual number of noises to be given in the experiment is multiplied by each of these numbers, the products will be the actual number of correct rejections and false alarms which would produce the highest percent correct. The actual number of hits and misses which would produce the highest percent correct can be computed in the same way. The area under the signal curve to the left of the criterion is the conditional probability of misses; the area under the signal curve to the right of the criterion is the conditional probability of hits. If the actual number of signals to be given in the experiment is multiplied by each of these numbers, the products will be the actual number of misses and hits which, when taken in conjunction with the correct rejections and false alarms, would produce the highest possible percent correct. Any other combination of the response contingencies would produce a lower percent correct.

Optimal bonuses earnable. When the z score position of the optimal beta and the d' are known, the optimal earnable bonus can be computed as shown in Tables 8 and 9.

In the example given, probability of signal is .50,

TABLE 6

OPTIMAL PERCENTS CORRECT WITH d' = 1.00

Beta = 3.00

	Total noises = 375 Criterion at +1.60		Total signals = 125 Criterion at +0.60	
	C/R	F/A	Hits	Misses
Conditional Probabilities	.94	.06	.27	.73
Actual number	352	23	34	91
Percent correct		77		

Beta = 0.33

	Total noises = 125 Criterion at -0.60		Total signals = 375 Criterion at -1.60	
	C/R	F/A	Hits	Misses
Conditional Probabilities	.27	.73	.94	.06
Actual number	34	91	352	23
Percent correct		77		

TABLE 7

OPTIMAL PERCENTS CORRECT WITH d' = 1.00

Beta = 1.00				
	Total noises = 250 Criterion at +0.50		Total signals = 250 Criterion at -0.50	
	C/R	F/A	Hits	Misses
Conditional Probabilities	0.69	0.31	0.69	0.31
Actual number	173	77	173	77
Percent correct		69		

TABLE 8

OPTIMAL EARNABLE BONUSES

Beta = 3.00

	Noises = 250 Criterion at +1.60		Signals = 250 Criterion at +0.60	
	C/R	F/A	Hits	Misses
Conditional Probabilities	0.95	0.05	0.27	0.73
Actual number	238	12	68	182
Values and costs	+3	-3	+1	-1
Matrix points	+714	-36	+68	-182
Bonus one-half cent per point		$2.82		

Beta = 0.33

	Noises = 250 Criterion at -0.60		Signals = 250 Criterion at -1.60	
	C/R	F/A	Hits	Misses
Conditional Probabilities	0.27	0.73	0.95	0.05
Actual number	68	182	238	12
Values and costs	+1	-1	+3	-3
Matrix points	+68	-182	+714	-36
Bonus one-half cent per point		$2.82		

TABLE 9

OPTIMAL EARNABLE BONUSES

Beta = 1.00				
	Noises = 250 Criterion at +0.50		Signals = 250 Criterion at -0.50	
	C/R	F/A	Hits	Misses
Conditional Probabilities	0.70	0.30	0.70	0.30
Actual number	175	75	175	75
Values and costs	+3	-3	+3	-3
Matrix points	+525	-225	+525	-225
Bonus one-half cent per point		$3.00		

beta = 3.00, and the criterion is at +1.60 z score units of the noise distribution and +0.60 z score units of the signal distribution. The area to the left of the criterion under the noise curve is the conditional probability of correct rejections (0.95); the area to the right of the criterion is the conditional probability of false alarms (0.05). The area to the left of the criterion under the signal curve is the conditional probability of misses (0.73); the area to the right of the criterion is the conditional probability of hits (0.27). If the number of noises delivered is multiplied by the conditional probabilities of correct rejections and of false alarms, the products are the actual number of correct rejections and false alarms which would have produced that criterion placement. The actual number of misses and hits can be determined in the same manner using the conditional probabilities of misses and hits and the number of signals delivered. If the actual number of occurrences of each response contingency is multiplied by values and costs of each, the net matrix points can be determined. The bonus is one-half cent per net matrix point. If the beta is a different value (as in the bottom of Table 8 and in Table 9), the criterion will be in a different position and the values and costs will be different but the procedure remains the same. If the probability of signal is something other

than .50, as it was in Experiment 1, the number of noises and signals will be different but the procedure remains the same.

Achieved betas

Given the conditional probabilities of false alarms and misses, the achieved betas can be computed with the help of a normal curve table, but the positions must be determined before the betas themselves can be found.

Positions of achieved betas. Enter the area column of a normal curve table with the conditional probability of correct rejections and read the position of the ordinate which would cut off that much area under the noise curve. Do the same thing with the conditional probability of hits to find the location of the criterion ordinate under the signal curve. Since the two curves are displaced by the amount of the d', the criterion will fall on different ordinates of the two curves.

If the height of the signal ordinate found above is divided by the height of the noise ordinate, the quotient will be the likelihood ratio (achieved beta) at the achieved criterion.

Losses in percent correct. The optimal percent correct minus the achieved percent correct will give the losses in percent correct.

Losses in bonuses earned. The optimal bonuses

earned minus the achieved bonuses earned will give the losses in bonuses earned.

Beta differences

Optimal betas minus achieved betas will give the beta differences.

Criterion placement errors (CPE)

Optimal position for the response criterion (position of optimal beta) minus the achieved position of the response criterion (position of achieved beta) will give the criterion placement error in z score of noise units.

APPENDIX C

ADDITIONAL DETAILS, APPARATUS AND DESIGNS

A block diagram of the apparatus set up is shown in Figure 1. All decibels mentioned below are relative to .0002 millibars. In both experiments the noise intensity was set so that the reading across the headset monitor box was .0062 volt with the noise attenuator zeroed. The attenuator was set to 47 decibels during the experiment, so estimating from the calibration charts of the earphones in the headset and taking into account the 600 cycles per second bandwidth, the noise intensity per one cycle band was 7.5 decibels. Signal intensities were derived in a similar way. In Experiment 1 when the signal interval was made long enough to register on a rms voltmeter the reading across the headset monitor box was .048 volt with the signal attenuator at 47 decibels. During the experiment the noise attenuator was set at 72 decibels. Estimating from the calibration charts in the headset, the signal intensity was 28 decibels. A different headset monitor box was put into the circuit between Experiments 1 and 2 because of a broken connection in the old one. It may

have had more internal resistance because test runs at the signal intensity used in Experiment 1 produced abnormally low d's. Therefore three calibration listeners were run at various signal intensities until an intensity was found which produced approximately the same d's as those found in Experiment 1. The reading across the headset monitor box with the signal attenuator zeroed was .062 volt.

Table 10 presents the experimental designs of Experiments 1 and 2 in tabular form. In Experiment 2 half of the listeners in each group were female.

TABLE 10

EXPERIMENTAL DESIGNS

Groups	Treatments (Optimal Betas)[a]			
	Practice	1	2	3
Experiment 1: Signal Probabilities				
Blind (N = 6)	1.00	0.33	1.00	3.00
Sighted (N = 6)	1.00	0.33	1.00	3.00
Experiment 2: Values and Costs				
Blind (N = 8)				
Mobile (N = 4)[b]	1.00	0.33	3.00	
Nonmobile (N = 4)[c]	1.00	0.33	3.00	
Sighted (N = 4)	1.00	0.33	3.00	

[a]Order of experimental treatments was counterbalanced.

[b]Had had a formal course in mobility.

[c]Had not had a formal course in mobility.

APPENDIX D

INSTRUCTIONS

Instructions for practice session, Experiment 1

Instructions were essentially the same as those used in Experiment 2 (see below), except that no matrix card was used and the audio tape was not used.

Instructions for experimental sessions, Experiment 1

Listeners were told that the session would be similar to the practice session and what the probability would be for the whole session.

Instructions for practice session, Experiment 2

The first seven paragraphs were similar to those read in Experiment 1 practice sessions. They were concerned with orientation to the room, the response apparatus, the feedback system, and a gradual decrease in intensity of the signal toward the level which would be used in the real experiment.

The listener was then handed the optimal beta equals 1.00 matrix card and it was briefly explained. The blind listeners were asked to actually read aloud their Braille cards so that the experimenter could be sure that they

understood that the matrix was in a grid pattern. The following instructions were then played into the sound resistant room from an audio tape:

"The following instructions are being delivered to you from a tape recording so that the instructions will be exactly the same for all the people who will be working with us on this project.

We are not yet back down to the intensity which we will use in the real experiment, but at this point we always tell the listener some more things.

First, you have probably already figured out that the order of signals and noises is completely random. We actually used a table of random numbers to choose the order. Therefore it is better not to try to guess what the next stimulus is going to be based on the previous ones. For example, if there have been a number of noises in a row, that does not mean that a signal is due.

Second, there are some tricks which make it more likely that you will be able to hear the signals when they get faint. You probably would have figured them out for yourself, but we have decided that it is simpler to tell all the listeners and let them use the tricks or not as they choose. The tricks are as follows: First, try not to breathe or swallow during the noise, or you may miss the signal. Some of the sighted listeners have found it useful

to close their eyes, and also, try not to move during the noise. Dragging the cable of the headset across the desk makes extra noise in the earphones, and just makes the task harder. You may use these tricks or not as you choose; we just routinely tell everybody.

The third point we want to make is that you will usually be able to make a few extra dollars at each session above your regular $1.50 per hour salary. The bonuses that you will earn will depend upon your responses. There are four possible combinations which will be explained.

Underneath the response apparatus there is a five by eight card which will help you to understand. Pick it up and examine it. Tell me when you have found it." Experimenter cuts in over the intercom and says that it was the card that the listener had already been given and that the experimenter would assume that he had it. "The bonuses that you will earn will depend upon your hits, misses, false alarms, and correct rejections. We can present to you either a noise or a signal. These are shown on the left hand side of your card. Look at them now. You can respond that you wish to bet that it was either a noise or a signal. Your responses are shown across the top of the card. You can look at them now. Therefore there are four possible combinations and these are shown in the middle of the card, that is, combinations of what we give and you say. A hit

is when we give a signal and you say signal, that is, you have hit the target. This is the upper left hand box in the middle of the card. In this part of the experiment you will earn three points for each one of those. A miss is if we give a signal and you say noise; you have missed the target. The miss is shown in the upper right hand box in the middle of the card. In this part of the experiment you lose three points for each one of those. A correct rejection is if we give a noise and you say that it is a noise; you have correctly rejected the idea that a signal was given. This is shown in the lower right hand corner in the middle of the card. In this part of the experiment you will earn three points for each one of those. A false alarm is if we give a noise and you say signal. This is shown in the lower left hand box in the middle of the card. You have, in a sense, false alarmed the presence of a signal. In this part of the experiment you will lose three points for each one of those. In general, in this part of the experiment, you earn three points for each hit and correct rejection, that is, each time you are correct; but you lose three points for each miss or false alarm, that is, each time you answer incorrectly. At the end of each block of trials we add up all the points you have earned, subtract from them all the points you have lost, and then pay you one-half cent for each point remaining. For example,

if at the end of a block you end up with 100 points, you earn a fifty cent bonus." Here the audio tape ended, listeners were asked if there were any comments or questions (there rarely were any), then the rest of the instructions were given to the listeners verbally, as follows.

Continue to reduce intensity of signal. Tell the listener that the experimenter will continue to gradually reduce the intensity of the signal during the next few trials. Increase the attenuation of the signal by one decibel each time the listener makes two hits, until attenuation reaches 70 decibels.

First block of 100 trials working for bonuses: The experimenter goes back into the sound resistant room. "We are not yet down to the intensity which will be used in the real experiment, but at this level we usually run 100 trials against the matrix, that is, you can make bonuses. Tell me when you are ready. I will start the apparatus, then when I am ready to start recording I will 'blip' the intercom twice but I will not say anything." At the end of this block and every block after this the experimenter will say "stop," figure out the bonus, and tell the listener the number of correct rejections, false alarms, hits, and misses he has made, his total percent correct, and the amount of his bonus.

Second block working for bonuses: If the listener

made less than 60 percent correct on the first block, the second block will be run at the same signal intensity, but if he makes better than 60 percent correct, the block will be run at 71 decibels of attenuation. "The signal will be a little less intense than it was on the previous block. Tell me when you are ready."

Water break: "At this time we usually take a short break and go upstairs for a drink of water."

Third block working for bonuses: This block is run at 71 decibels of attenuation. (a) (Same intensity or different intensity) If the previous block was run at 70 decibels of attenuation, the listener will be told that the signal intensity will be slightly less intense than it was on the first block. If the previous block was run at 71 decibels of attenuation, the listener was told that the signal intensity would be the same as the previous block. (b) Warm up trials. The listener will also be told that the first few signals will be easy to hear, but they will fairly quickly be turned down and when they reach the level for this block the experimenter will "blip" the intercom twice to indicate that he has begun recording responses. This warmup procedure will be continued at the beginning of each block for the rest of the experiment. The warm up trials will all be started at 65 decibels of attenuation and then turned down one decibel approximately each time

the listener makes a hit.

Fourth block working for bonuses: This block is run at 72 decibels of attenuation. "The signal will be a little less intense than it was during the previous block of trials."

Instructions for experimental sessions, Experiment 2

Listeners were told that the session would be similar to the previous one. They were given the appropriate matrix card, it was briefly explained, and then the appropriate audio tape from among those transcribed below was played into the sound resistant room.

(a) Beta equals 0.33: "Today's session will be similar to the last one you had here; your bonus will depend upon your responses. However, it will be calculated slightly differently. Under the response apparatus there is a five by eight card which will help you to understand the value of the different responses. Pick it up and examine it. Tell me when you have found it." The experimenter cuts in over the intercom and says that it was the card that the listener had already been given and that the experimenter would assume that he had it. "You will notice that the stimuli we can give, noise or signal, are again shown along the left hand side of the card. Your responses, noise or signal, are shown across the top of the card, and

the four possible combinations of the two events are shown in the middle of the card. The upper left hand block shows a hit, that is, we give signal and you say signal. You will note that during this session each hit will be worth plus three points. The upper right hand block shows a miss, that is, we give signal and you say noise. Note that during this session each miss will cost you three points. The lower left hand block shows a false alarm, that is, we give noise and you say signal. Note that each false alarm will cost you one point. The lower right hand block shows a correct rejection, that is, we give noise and you say signal. Note that each correct rejection will be worth plus one point. Notice that the reward for hits, and the penalty for misses, are higher than the reward for correct rejections and the penalty for false alarms. This means that you will earn the most money if you try to make as many hits as you can; try not to miss too many signals. On the other hand you must not make too many false alarms either, because each one will reduce your earnings a little bit. At the end of the session your plus scores will be added up. We will subtract from them all your minus scores and you will be paid one-half cent for each point remaining."

(b) Beta = 3.00: Instructions are the same as those for the beta = 0.33 treatment as given above except that

the values and costs for the response contingencies are appropriate for the 3.00 treatment. The last section of the instructions for the beta = 3.00 treatment is as follows. "Notice that the reward for correct rejections and the penalty for false alarms are higher than the reward for hits and the penalty for misses. This means that you will earn the most money if you try to make as many correct rejections as you can; try not to false alarm too many signals. On the other hand you must not make too many misses either, because each one will reduce your earnings a little bit. At the end of the session your plus scores will be added up. We will subtract from them all your minus scores and you will be paid one-half cent for each point remaining."

APPENDIX E

SUMMARY TABLES OF RESULTS

TABLE 11

ANALYSIS OF VARIANCE OF d's BETWEEN MOBILE AND NONMOBILE BLIND IN THE EXPERIMENT 2 TREATMENT WHERE BETA EQUALLED 3.00

Source	df	MS	F
Between Groups	1	0.1840	2.655
Within Groups	6	0.0693	

TABLE 12

ANALYSIS OF VARIANCE OF d's BETWEEN BLIND AND SIGHTED IN THE EXPERIMENT 1 TREATMENT WHERE BETA EQUALLED 0.33

Source	df	MS	F
Between Groups	1	0.060	0.363
Within Groups	10	0.165	

TABLE 13

WITHIN SESSION VARIABILITY OF CRITERION PLACEMENT AMONG THE NONMOBILE BLIND

Listener	First Session	Second Session
J. K.	0.21	0.12
G. D.	0.19	0.16
J. H.	0.13	0.55
G. B.	0.38	1.08

Note.--Table entries are standard deviations of the means of the betas achieved in each of the five blocks of each session.

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